Assessment of Urban Aerial Taxi with Cryogenic Components under Design Environment for Novel Vertical Lift Vehicles (DELIVER)

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Assessing the potential to bring 100 years of aeronautics knowledge to the entrepreneur's desktop to enable a design environment for emerging vertical lift vehicles is one goal for the NASA's Design Environment for Novel Vertical Lift Vehicles (DELIVER). As part of this effort, a system study was performed using a notional, urban aerial taxi system to better understand vehicle requirements along with the tools and methods capability to assess these vehicles and their subsystems using cryogenic cooled components. The baseline was a vertical take-off and landing (VTOL) aircraft, with all-electric propulsion system assuming 15 year technology performance levels and its capability limited to a pilot with one or two people and cargo. Hydrocarbon-fueled hybrid concepts were developed to improve mission capabilities. The hybrid systems resulted in significant improvements in maximum range and number of on demand mobility (ODM) missions that could be completed before refuel or recharge. An important consideration was thermal management, including the choice for air-cooled or cryogenic cooling using liquid natural gas (LNG) fuel. Cryogenic cooling for critical components can have important implications on component performance and size. Thermal loads were also estimated, subsequent effort will be required to verify feasibility for cooling airflow and packaging. LNG cryogenic cooling of selected components further improved vehicle range and reduced thermal loads, but the same concerns for airflow and packaging still need to be addressed. The use of the NASA Design and Analysis of Rotorcraft (NDARC) tool for vehicle sizing and mission analysis appears to be capable of supporting analyses for present and future types of vehicles, missions, propulsion, and energy sources. Further efforts are required to develop verified models for these new types of propulsion and energy sources in the size and use envisioned for these emerging vehicle and mission classes.

Nomenclature

DELIVER	=	Design Environment for Novel Vertical Lift Vehicles
DGW	=	design gross weight
Genset	=	engine + generator
ISA	=	international standard atmosphere
l	=	liter
LNG	=	liquid natural gas
NDARC	=	NASA Design and Analysis of Rotorcraft
nmi	=	nautical mile
ODM	=	on demand mobility
OGE	=	out of ground effect
SOA	=	state of the art
V_{be}	=	best endurance velocity
V_{br}	=	best range velocity
VTOL	=	vertical take-off and landing
η	=	efficiency

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I. Introduction

The Design Environment for Novel Vertical Lift Vehicles (DELIVER) subproject goals are to assess the potential of developing methods and tools that incorporate validated, prior design knowledge for conventional, as well as potential future systems to enable a variety of users to use the design environment for emerging vertical-lift vehicles. Rather than the present methodology of build and fly (and repeat), can a majority of the design effort be accomplished quickly, effectively, and with reasonable accuracy via advanced design tools? Can these tools also be validated via focused, supporting hardware / software research efforts? Current tools for vehicle sizing and mission analysis and their component performance have been validated for current vehicles, missions and subsystems. However, there are limited models for advanced vehicle configurations, powered with either all-electric or hybrid-electric propulsion systems, including cryogenic-cooled components. Therefore, a system study was performed to assess the feasibility to capture many of these aspects for a design problem of interest: an urban aerial taxi that might include cryogenic components. The vehicle concept will be covered first, noting important design requirements for capability and internal layout. Next, the motive propulsion and energy systems will be examined, including performance levels assumed for this study, as well as some discussion concerning unique features. Then, the analysis methodology section will explain the various study assumptions, the specific tools and vehicle models. Finally, results will be presented, potential future efforts will be proposed, and some final conclusions given.

II. Baseline Vehicle

A. Baseline Vehicle Selection and Description

For the urban aerial taxi market, VTOL capabilities and operations are critical factors to help define the baseline vehicle. Recent studies such as References 1 and 2 indicate that hover-optimized designs, generally representative of single-main rotor helicopters, are not the best study candidates while considering both this mission and hybridization at assumed system performance levels. Therefore, a more cruise optimized, all-electric VTOL aircraft was chosen; a representative image is shown in Figure 1. The all-electric, VTOL aircraft is a hybrid helicopter / airplane design, that is enabled by advances in distributed electric propulsion technologies. Payload capability was selected as one or two passengers (450 lb., 205 kg maximum total payload) with a 200 pound (91 kg) pilot. Approximately one hour flight duration seemed appropriate for aircraft sizing, which led to the design mission range being set to 150 nautical miles. This was thought to enable some number of 20 and 50 nautical mile ranges missions for on demand mobility (ODM) capability. More details concerning the vehicle, missions, and subsequent results will be covered in subsequent sections.

Figure 1. Notional VTOL vehicle image.

B. Vehicle and Propulsion Layout

Figure 2 shows a notional layout including some of the major systems to better understand packaging aspects. A distributed arrangement of the various battery packs and power electronics might be more effective to isolate faults and get some benefit from span loading these systems and their thermal management features. This might especially be true for passive, distributed, thermal management systems. Since it was believed that active systems would likely be required, as well as facilitate the design for cryogenic cooled systems, batteries and most power electronics were envisioned to be in the main body of the aircraft. This could make battery replacement easier, as well as facilitate design and substitution of the all-battery system and power electronics with a hybrid system using hydrocarbon fuels. The added weight of the hybrid system could be offset by reducing the battery size and capability, supplemented by an energy-dense, hydrocarbon genset (engine + generator). Such a tradeoff could enable

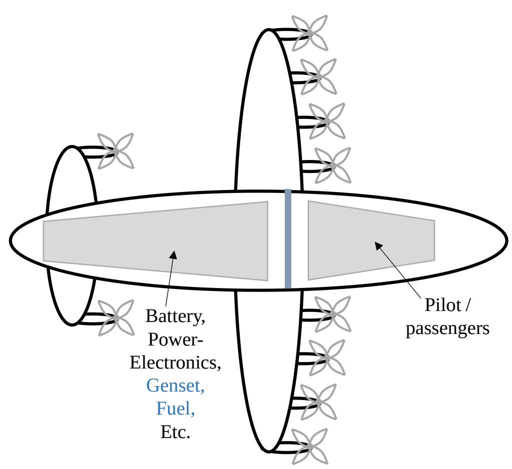

FIGURE 2. Notional vehicle layout

greater range and potentially other system capabilities. Using a hybrid genset could also serve to insure some vehicle capability if desired battery advances are not realized during vehicle development. Propulsion, power and energy systems are discussed in the next section.

III. Propulsion and Energy Concepts

Reference 3 reported on present status and future potential for various, noncryogenic, hybrid electric components. Impressive improvements in electric motor efficiency and power to weight offer an opportunity for new and more capable aviation vehicles. However, widespread adoption of all electric systems is still hampered by the much lower electrical energy density for batteries. Previous efforts[2,4] highlighted the performance of advanced diesel engines as primary power and in hybrid systems for vertical lift vehicles to mitigate this deficiency. This is illustrated in Table 1, where the much lower efficiency of the diesel cycle is more than compensated by the high energy density of its hydrocarbon fuel. These characteristics suggest all-electric designs can be viable solutions for vehicles and missions that require high power, but less stringent duration or total energy requirements.

Table 1. Example engine / energy storage characteristics. (Study values **highlighted**).

Engine type	Power / weight, hp/lb. (kW/kg)	η, %	Fuel, energy density, MJ/kg (Wh/kg)	Net energy density, MJ/kg (Wh/kg)
all-electric, SOA*	1.9 (3.1)	85	0.70 (194)	0.60 (165)
15 year	**3.4 (5.6)**	**93**	**1.75 (486)**	**1.63 (450)**
30 year	4.9 (8.0)	97	3.15 (875)	3.06 (850)
Diesel cycle, SOA	0.53 (0.9)			
15 year	**1.06 (1.8)**	**37**	**Diesel, 43.0 (12,000)**	**15.9 (4,400)**
30 year	1.59 (2.7)			

* For electric systems, "Fuel" is lithium battery, cell only average of lithium ion and sulfur technologies
Electric system power to weight for electric motor reported at 3, 8, and 16 hp/lb. and power electronics at 5,6, and 7 hp/lb. for state of the art (SOA), 15 and 30 year technology assumptions (from Reference 3).

A. Baseline Propulsion Concept

The baseline, all-electric system seems fairly straightforward when represented by a simple architecture block diagram as shown in Figure 3. As indicated in Figures 1 and 2, the electric motors and rotors are distributed throughout the vehicle. That can also be true for the batteries and power electronics, to isolate faults, for weight and load sharing, and other aspects. However, as mentioned previously, the battery and power electronics were positioned in the main fuselage, to facilitate conversion from all-electric to hybrid and to facilitate comparisons in subsequent efforts.

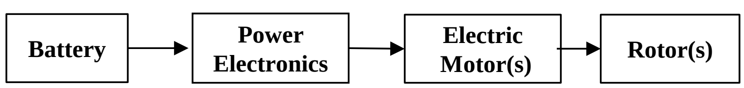

Figure 3. Baseline, all-electric propulsion architecture block diagram.

B. Advanced Diesel Hybrid

The advanced diesel hybrid propulsion architecture is assumed to be a series hybrid and is represented in Figure 4. A tradeoff in genset power versus battery is possible to vary range, hover or other operational capability. The battery was downsized to only augment the genset to meet high power situations, such as vertical take-off and landing. This reduces battery size and weight, although it also limits maximum time in vertical lift mode. The power electronics can also be designed to recharge the battery from the fueled genset during flight (depending on genset capability and vehicle power requirements). The weight for the power electronics includes the system for the vehicle's electric motors driving the rotors, as well as the system required for the genset. In both cases, power electronics weights were based on each system's maximum power handling, assuming a value of 1 lb. per 6 hp suggested by Reference 3, with plans for subsequent efforts to go into more detailed layouts and thermal analyses to verify study assumptions.

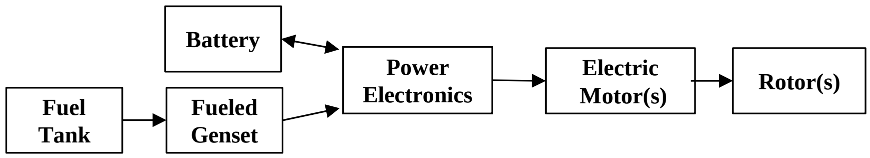

Figure 4. Advanced diesel series hybrid propulsion architecture block diagram.

C. Advanced Diesel Hybrid using Liquid Natural Gas (LNG) to Cryogenically Cool Components

Using Liquid Natural Gas (LNG) to cryogenically cool components can be advantageous depending on the vehicle and its propulsion and power system arrangement. The cryogenic LNG is used for the thermal management of the co-located power electronics and genset generator, with the potential to realize electric system performance and weight improvements; while also reducing or eliminating some component cooling airflows. Additional improvements are realized for the overall system from the higher heating value (per fuel weight) of the LNG and slightly greater genset output power for a given fueled engine size (the result from less electric component losses). Work is still underway to define the specific characteristics for this system and will be reported in subsequent efforts. For the purposes of this study, the various electric component weight assumptions for conventional cooling systems were used for LNG cooled components. The LNG fuel tank properties have been estimated assuming one inch foam insulation over a lightweight metal pressure vessel resulting in one pound LNG tank weight per six pounds fuel. The thermal losses for the power electronics and generator are essentially zero (0.5%), with any losses and recovered and used in fuel. Updates in thermal management with LNG cooling are discussed in the next section.

IV. Analysis Methods

A. Analysis Tools

The design code NASA Design and Analysis of Rotorcraft (NDARC, References 5-8) was used to model the various vehicle and propulsion systems, performing vehicle sizing and performance analysis. As described in Reference 8, NDARC's propulsion models were expanded to include additional propulsion and power system concepts, including those necessary for electric propulsion components and hybrid systems. The vehicle and mission models were developed from the tilt rotor example distributed with NDARC v1.10. The actual sizing model for the VTOL aircraft was already available from previous efforts,[2,9] but was updated to slightly reduce its design disk loading and hover power requirement. Its sizing mission range was maintained at 150 nautical miles (resulting in roughly an hour mission time). Genset sizing and mission profile used for this effort are discussed in the next sections.

B. Genset Engine and Vehicle Battery Sizing

The aircraft power versus velocity is given in Figure 5. Noted in the figure are best endurance velocity (V_{be}) and best range velocity (V_{br}). Since there was not a large variation in the power at these two flight points, hydrocarbon-fueled engine sizes of 150, 175, and 200 hp (112, 131, and 150 kW) were chosen. The smallest power output is a little below best endurance power, but offered the potential to match fueled and electrical energy usage over various missions at V_{be} as well as minimize engine and generator size (to determine if such sizing is advantageous). The largest (200 hp) genset can generate enough power for cruising at V_{br} and also recharge the battery. This could result in a vehicle that would only need re-fueling for continuous operation over one or several missions, as opposed to also requiring battery recharging facilities at selected landing destinations. Values from Table 1 were used to estimate battery weights. An additional 20% weight was included for the battery management system, with any power required for the battery management system included in the losses for power electronics.

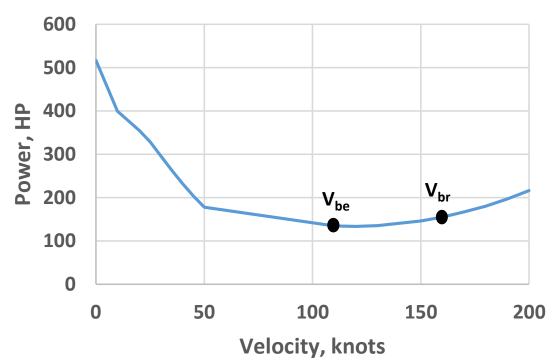

Figure 5. Aircraft power versus velocity.

C. Mission Profile for Sizing and Performance

The simple mission profile shown in Figure 6 was used with a 150 nautical mile range to size the baseline, all-electric VTOL and determine maximum range for other propulsion combinations. For the baseline, all-electric vehicle, cruise speed was set to V_{br}. Initial performance runs suggested that 5,000 ft., ISA was a more efficient cruising altitude; however, because the descent was not explicitly modeled, any benefit from the higher cruise altitude was more than offset by higher climb energy. Cruise altitude was therefore set to 2,000 ft., ISA. For the maximum range mission, two operational methods were used to determine maximum range for the hybrid-electric systems. First, if the maximum genset power output was less than V_{br} cruise requirements, the nominal maximum range mission would be battery energy limited, with fuel remaining beyond 10% reserves. For those cases, the operational method used was a combination of operation at V_{br} and V_{be} to truly maximize range with 10% reserves of initial fuel and battery charge. The second would be if the maximum genset power was greater than that required for V_{br} cruise. In that case, optimally set genset power to maximize range with the 10% required fuel and battery energy reserves.

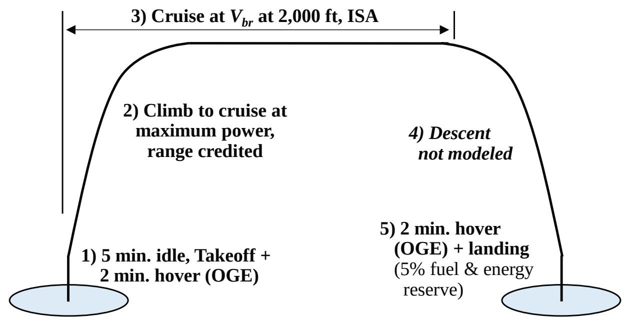

Figure 6. Baseline sizing and maximum range mission profile.

To try and simulate ODM operations, assume repeated mission profiles at 20 or 50 nautical mile range at V_{br}, which would minimize total energy and user flight time. Hold time between missions was the time to self-recharge batteries to full. Missions were run until fuel reached 10% of initial, design fuel load. The time to recharge the all-electric at its maximum rate was also estimated.

D. Thermal Management

Table 2. Electric motor and power electronics efficiencies (from Ref. 3).

Technology year	Motor η, %	Power electronics η, %	Net η, %	Total loss, %
SOA	90	94	85	15
15 year	95	98	93	7
30 year	98	99	97	3

Another important consideration for electric vehicles is thermal management. Table 2 gives state of the art (SOA) and projected efficiencies for electric motors, generators and the power electronics. Although very high compared to advanced heat engines, system design must include some considerations for cooling. Thermal management for the electric motors driving the rotors was not included in this effort, although their efficiency and losses were included in vehicle and mission energy totals. To estimate cooling airflow requirements for all other component, a simple methodology similar to Reference 10 was used. Cooling airflow exhaust temperature was assumed to be 60% of the temperature difference between ambient and each component's maximum temperature capability. Subsequent efforts could perform more detailed design and analysis to improve performance and weight estimates. For the genset engine cooling system, generator and all other power electronics, 220°F (105°C) maximum temperature capability was assumed. Battery maximum use temperature was assumed to be 140°F (60°C). For the heat load from the genset diesel engine, analysis reported in Reference 11 indicated losses were roughly equally split between the exhaust (no cooling required) and that which would have to be actively removed. Since diesel efficiency was assumed to be 37%, cooling would be 31.5% of fuel energy (or equal to 85% of the diesel work output, although as heat to be removed). For the power electronics, Table 2 suggested about 2% loss for the non-LNG system. For battery heat loads, the default lithium battery model with losses from NDARC was used. For the cryogenic cooled components, the generator, and all power electronics were assumed to be 99.5% efficient, with losses captured within the LNG fuel used by the genset engine. For actual power levels and ambient conditions, output from the NDARC mission analyses were used.

V. Results and Discussion

Payload capability was assumed constant among variants, therefore design gross weight, or empty plus fuel weight was held constant among the concepts. Selected vehicles and specifications are given in Table 3. For the genset sizes from 150 to 200 hp (112 – 150 kW), it was almost an equal trade from battery to genset power, with a little over roughly 210 pounds (≈ 95 kg) available fuel for all the hybrid cases. This also resulted in the hybrid versions having

7 to 8 times more energy than the all battery cases, which is reflected in the hybrid's enhanced capabilities that are discussed a little later. Another item to note is the much larger fuel volume for the LNG pressurized tank. That is a combination of the much lower density of LNG versus diesel fuel itself (3.5 lb./gallon versus 6.84 lb./gallon) and other factors for the LNG system. As the LNG system is envisioned, some vapor volume is required in the LNG tank (maximum liquid fill to 90%), as well as the one inch, external foam insulation (which is about 18% of total tank volume at the desired fuel load).

Table 3. Selected Vehicle Specifications.

Vehicle → / Parameter ↓	All-Electric Baseline	150 hp conventional cooled hybrid	200 hp cryo-cooling assisted hybrid
Design gross weight (DGW), lb. (kg)	3,676 (1,671)	3,678 (1,672)	3,673 (1,669)
Empty weight, lb. (kg)	3,021 (1,373)	2,813 (1,279)	2,788 (1,267)
Disk loading / wing loading, lb./ft^2	10 / 50	10 / 50	10 / 50
Genset Weight, lb. (kg), % DGW	0	211 (96), 6%	256 (116), 7%
Nominal fuel weight, lb. (kg), % DGW *	0	210 (95), 6%	230 (105), 6%
Fuel Energy, MJ	0	4,096	4,695
Fuel volume, gallon, (l)	0	30.7 (116)	89.1 (337)
Battery + BMS weight, lb. (kg), % DGW *	919 (418), 25%	498 (226), 13.5%	437 (199), 12%
Battery energy, MJ	609	330	290
Battery volume, gallon, (l)	80.4 (304)	43.6 (165)	38.3 (145)
Sea level maximum rated power, hp (kW)	578 (431)	578 (431)	578 (431)
Propulsion engines and power electronics weight, lb. (kg), % DGW	307.3 (140), 8%	310 (141), 8%	312 (141), 8%

A. Mission Range and Number of ODM Missions

Mission range results are given in Table 4. The significantly higher energy density of the hydrocarbon fuels results in significantly greater maximum range than the all-battery baseline, as well as significantly more ODM mission capability before recharge / refuel. Although the number of ODM missions should really be integer, one decimal is included. This should indicate if the vehicle design was just able to accomplish the given number of missions (with the last mission not necessarily for revenue, but to get to a refueling depot); versus enough potential to make a shorter trip to "well-positioned" refueling depots. Larger genset power improved maximum range (more time at best range, as opposed to a less optimal speed), sometimes gave additional ODM missions and definitely reduced the hold time between missions. The reduced electric component losses with LNG cryogenic cooling also added some benefits for range, number of ODM missions, and hold time between missions. For the all-electric baseline, an external charger would be required; recharge time and power level at an assumed 3C charge rate is also given in Table 4. For the ODM

Table 4. Maximum range and multiple ODM mission results.

Vehicle→	Baseline	Conventional hybrid			Cryogenically cooled hybrid		
		150 hp	175 hp	200 hp	150 hp	175 hp	200 hp
Maximum range missions							
All V_{br}, nmi	150	298*	460*	496	378*	530*	580
Mix of V_{br} and V_{be}, nmi	122 (all V_{be})	470	492		554	575	
Multiple ODM missions							
Number of 20 nmi missions	3	6.5	6.9	7.3	7.8	8	8
Hold time, minutes †	7 ‡	30	21	15	27	18.5	13
Number of 50 nmi missions	2	4	4.6	4.9	5.3	5.6	7
Hold time, minutes †	10 ‡	36	22	15	31	19	12

* Battery energy limited range
† Time on ground between ODM missions to self-recharge battery to full
‡ No self-recharge capability, 3C / 500 kW charger required

missions, from missions segment 1 (initial taxi) to end of segment 5 (landing), total time was about 17 minutes for the 20 nautical mile range and 28 minutes for 50 nautical mile range missions.

B. Thermal Management Estimates

Preliminary thermal estimates were made for all vehicles, although details will only be reported for a representative set of vehicles and most relevant flight conditions from the mission profile shown in Figure 6. Vehicles chosen were the same as those given in Table 3, the baseline all-electric, 150 hp conventionally cooled hybrid, and 200 hp cryo-cooling assisted hybrid, with results shown in Tables 5, 6, and 7, respectively. One important difference between vehicles propelled by all-electric versus air-breathing engines is that the electric motors driving the rotors do not lapse power with high altitude or hot day. Their thermal management systems must be designed for the 30-40% increased cooling airflow rates required (because of the hotter and less dense air) or intelligent flight controls must limit vehicle operations to maintain the electric components operation within valid temperature limits. The hover and climb segments are the most thermally taxing, although the climb could be performed at lower power levels. The climb is performed here at maximum power, as that is the most efficient and presently not limited by thermal considerations. Battery cooling requires significantly more airflow for high / hot conditions, as the batteries have a significantly lower, maximum use temperature than that assumed for the power electronics.

Table 5. Baseline, All-Electric Thermal Load Estimates.

Mission segment →	1) hover (OGE)	2) climb (start)	2) climb (end)	3) cruise
Standard Day, ISA				
Battery Cooling				
Thermal load, hp (kw)	35 (26)	35 (26)	35 (26)	3 (2)
Cooling airflow, ft^3/min. (l/s)	1665 (786)	1655 (781)	1614 (762)	151 (72)
Power electronics				
Thermal load, hp (kw)	10 (7)	10 (7)	10 (7)	3 (2)
Cooling airflow, ft^3/min. (l/s)	232 (109)	231 (109)	235 (111)	72 (34)
High, hot (5,000ft, ISA+20°C)				
Battery Cooling				
Thermal load, hp (kw)	35 (26)	35 (26)	35 (26)	3 (2)
Cooling airflow, ft^3/min. (l/s)	2668 (1259)	2652 (1252)	2535 (1196)	238 (112)
Power electronics				
Thermal load, hp (kw)	10 (7)	10 (7)	10 (7)	3 (2)
Cooling airflow, ft^3/min. (l/s)	325 (153)	324 (153)	328 (155)	101 (47)

A few things to note here concerning the hybrid cases: Cooling requirements and airflow are dominated by the diesel engine cooling. No genset power lapse with high / hot conditions was assumed; this would be true for a turbocharged diesel (if not past the thermal breakpoint), but such operation would change airflow cooling requirements. Next, battery cooling requirements are similar among the hybrids and the all-battery baseline. The baseline is sized for 150 nautical mile range, so its battery pack is only at 2C discharge during vertical mode. For the hybrid systems, it was sized for maximum 3C discharge to minimize battery weight and size. This results in similar battery heat generation for the hybrid vehicles, even though total battery draw is at 25-36% less power. The improved efficiencies for LNG cryogenic cooled components resulted in significantly lower power electronics thermal load, with any thermal loads captured and used by the fuel.

Table 6. 150 hp Conventional Cooled Hybrid Thermal Load Estimates.

Mission segment →	1) hover (OGE)	2) climb (start)	2) climb (end)	3) cruise
Standard Day, ISA				
Battery Cooling				
Thermal load, hp (kw)	35 (26)	35 (26)	35 (26)	0 (0)
Cooling airflow, ft^3/min. (l/s)	1672 (789)	1658 (783)	1617 (763)	11 (5)
Power electronics				
Thermal load, hp (kw)	10 (7)	10 (7)	10 (7)	3 (2)
Cooling airflow, ft^3/min. (l/s)	232 (109)	231 (109)	235 (111)	76 (36)
Hybrid Genset Cooling				
Thermal load, hp (kw)	118 (88)	118 (88)	118 (88)	118 (88)
Cooling airflow, ft^3/min. (l/s)	2797 (1320)	2797 (1320)	2843 (1342)	2843 (1342)
High, hot (5,000ft, ISA+20°C)				
Battery Cooling				
Thermal load, hp (kw)	35 (26)	35 (26)	35 (26)	0 (0)
Cooling airflow, ft^3/min. (l/s)	2680 (1265)	2657 (1254)	2540 (1199)	17 (8)
Power electronics				
Thermal load, hp (kw)	10 (7)	10 (7)	10 (7)	3 (2)
Cooling airflow, ft^3/min. (l/s)	325 (153)	324 (153)	328 (155)	106 (50)
Hybrid Genset Cooling				
Thermal load, hp (kw)	118 (88)	118 (88)	118 (88)	118 (88)
Cooling airflow, ft^3/min. (l/s)	3916 (1848)	3916 (1848)	3970 (1874)	3970 (1874)

Table 7. 200 hp Cryo-Cooling Assisted Hybrid Thermal Load Estimates.

Mission segment →	1) hover (OGE)	2) climb (start)	2) climb (end)	3) cruise
Standard Day, ISA				
Battery Cooling				
Thermal load, hp (kw)	30 (22)	30 (22)	30 (22)	0 (0)
Cooling airflow, ft^3/min. (l/s)	1417 (669)	1407 (664)	1372 (647)	7 (3)
Power electronics*				
Thermal load, hp (kw)	4 (3)	4 (3)	4 (3)	3 (2)
Hybrid Genset Cooling				
Thermal load, hp (kw)	151 (112)	151 (112)	151 (112)	151 (112)
Cooling airflow, ft^3/min. (l/s)	3574 (1687)	3574 (1687)	3632 (1714)	3632 (1714)
High, hot (5,000ft, ISA+20°C)				
Battery Cooling				
Thermal load, hp (kw)	30 (22)	30 (22)	30 (22)	0 (0)
Cooling airflow, ft^3/min. (l/s)	2271 (1072)	2253 (1064)	2154 (1017)	10 (5)
Power electronics*				
Thermal load, hp (kw)	4 (3)	4 (3)	4 (3)	3 (2)
Hybrid Genset Cooling				
Thermal load, hp (kw)	151 (112)	151 (112)	151 (112)	151 (112)
Cooling airflow, ft^3/min. (l/s)	5003 (2361)	5003 (2361)	5073 (2395)	5073 (2395)

* Cooling for power electronics by LNG fuel (no additional airflow required)

Further studies including more detailed layout and thermal analyses are needed for the propulsion and power components to verify these preliminary results. As learning and modeling improves, these improvements should also be applied to the models being developed for use in vehicle sizing and mission analysis. Recent upgrades to the vehicle sizing and mission analysis tool applied in this study indicate that it is capable of supporting analyses for these new types of vehicles, missions, propulsion, and energy sources. However, efforts are required to develop verified models for these new types of propulsion and energy sources, in the size and use cases envisioned for these emerging vehicle and mission classes.

VI. Conclusion

Assessing the potential to bring 100 years of aeronautics knowledge to the entrepreneur's desktop enabling a design environment for emerging vertical lift vehicles is one goal for the NASA's Design Environment for Novel Vertical Lift Vehicles (DELIVER). As part of this effort, a system study was performed using a notional, urban aerial taxi system to better understand vehicle requirements along with the tools and methods capability to assess these vehicles and their subsystems using cryogenic cooled components. The vehicle was assumed to have a pilot with one or two passengers, some cargo and vertical take-off and landing (VTOL) capability. The baseline propulsion was all-electric, assuming 15 year electric and battery technology levels. Hybrid propulsion, using various sizes for diesel engines + generator (genset) to replace some of the battery were also explored. Thermal loads and their management were also considered, using conventional air cooling and liquid natural gas (LNG) cryogenic cooling of selected components.

The hybrid systems resulted in significant improvements in maximum range and number of on demand mobility (ODM) missions that could be completed before refuel or recharge. While thermal loads were estimated in this study, subsequent effort are required to verify that the airflow required and component packaging is viable. LNG cryogenic cooling of selected components further improved vehicle range and reduced thermal loads, but the same concerns for airflow and packaging still need to be addressed.

The use of the NASA Design and Analysis of Rotorcraft (NDARC) tool for vehicle sizing and mission analysis appears to be capable of supporting analyses for present and future types of vehicles, missions, propulsion, and energy sources. Further efforts are required to develop verified models for these new types of propulsion and energy sources, in the size and use envisioned for these emerging vehicle and mission classes.

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